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Deep *Chandra* observations of TeV binaries – I. LSI +61°303

N. Rea,^{1★†} D. F. Torres,^{1,2} M. van der Klis,³ P. G. Jonker,^{4,5} M. Méndez⁶
and A. Sierpowska-Bartosik⁷

¹*Institut de Ciències de l'Espai (ICE, IEEC–CSIC), Campus UAB, Fac. de Ciències, Torre C5-parell, 2a planta, 08193 Barcelona, Spain*

²*Institució Catalana de Recerca i Estudis Avançats (ICREA), Barcelona, Spain*

³*University of Amsterdam, Astronomical Institute “Anton Pannekoek”, Postbus 94249, 1090 GE Amsterdam, the Netherlands*

⁴*SRON-Netherlands Institute for Space Research, Sorbonnelaan 2, 3584 CA Utrecht, the Netherlands*

⁵*Harvard-Smithsonian Center for Astrophysics, 60 Garden Street, Cambridge, MA 02138, USA*

⁶*Kapteyn Astronomical Institute, University of Groningen, PO Box 800, 9700 AV Groningen, the Netherlands*

⁷*University of Lodz, Department of Astrophysics, Pormorska Street 149/153, PL-90236 Lodz, Poland*

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ABSTRACT

We report on a 95 ks *Chandra* observation of the TeV emitting high-mass X-ray binary LSI +61°303, using the ACIS-S camera in continuous clocking mode to search for a possible X-ray pulsar in this system. The observation was performed while the compact object was passing from phase 0.94 to 0.98 in its orbit around the Be companion star (hence close to the apastron passage). We did not find any periodic or quasi-periodic signal (at this orbital phase) in a frequency range of 0.005–175 Hz. We derived an average pulsed fraction (PF) 3σ upper limit for the presence of a periodic signal of $\lesssim 10$ per cent (although this limit is strongly dependent on the frequency and the energy band), the deepest limit ever reached for this object. Furthermore, the source appears highly variable in flux and spectrum even in this very small orbital phase range, in particular we detect two flares, lasting thousands of seconds, with a very hard X-ray spectrum with respect to the average source spectral distribution. The X-ray PF limits we derived are lower than the PF of any isolated rotational-powered pulsar, in particular having a TeV counterpart. In this scenario, most of the X-ray emission of LSI +61°303 should necessarily come from the interwind or innerpulsar wind zone shock rather than from the magnetosphere of the putative pulsar. On the other hand, very low X-ray PFs are not unseen in accreting neutron star systems, although we cannot at all exclude the black hole nature of the hosted compact object, a pulsar with a beam pointing away from our line of sight or spinning faster than ~ 5.6 ms, nor that pulsations might have a transient appearance in only a small fraction of the orbit. Furthermore, we did not find evidence for the previously suggested extended X-ray emission.

Key words: stars: individual: LSI +61°303 – X-rays: binaries.

1 INTRODUCTION

High-mass X-ray binaries (HMXBs) are relatively young ($< 10^7$ yr) systems composed of a massive OB-type star and a compact object, either a neutron star or a black hole. These systems are generally bright X-ray emitters, due to matter from the OB star accreting on to the compact object. The majority of the HMXBs are Be/X-ray binaries, and some tens of them are O main-sequence or supergiant X-ray binary systems. Accretion takes place through either the strong stel-

lar wind of the optical companion or Roche lobe overflow, where matter flows via the inner Lagrangian point and an accretion disc to the compact object (see Frank, King & Raine 1992). A powerful X-ray source ($L_X \sim 10^{35} - 10^{38}$ erg s⁻¹) is produced, which ionizes almost the whole stellar wind. The X-ray continuum spectra of HMXBs are often described by a power law with photon index $\alpha \sim 1-2$ (modified at higher energies by an exponential cut-off). A spectrum of this form can be produced by inverse Compton scattering of soft X-rays by hot electrons in the accretion column near the compact object, and a part of this emission is scattered by the stellar wind of the massive companion. This might sometimes result in a further non-thermal spectral component, but with a different absorption column depending on the orbital phase of the system.

★Ramon y Cajal Research Fellow.

†E-mail: rea@ieec.uab.es

Furthermore, in some HMXBs a soft excess at $\sim 0.1\text{--}2$ keV is detected, very common in systems hosting pulsars (Hickox, Narayan & Kallman 2004).

On top of the continuum model, spectral lines are often present in these systems, neutral and ionized, such as Fe, Si, Mg, Ar, N, Ca, mainly produced in the stellar wind or in the accretion disc (if any) illuminated by the strong X-ray emission of the compact object (see e.g. Cottam et al. 2001; van der Meer et al. 2005).

To date, there are only four or five binary systems known to be emitting up to TeV energies, all of them of the HMXB class: PSR B1259–63 (Aharonian et al. 2005a), LSI+61°303 (Albert et al. 2006), LS 5039 (Aharonian et al. 2005b, 2006), Cyg X-1 (Albert et al. 2007) and possibly the newly suggested candidate HESS J0632+057 (Aharonian et al. 2007, Hinton et al. 2009). These sources are rather peculiar with respect to the HMXB class. The first identified TeV binary system was PSR B1259–63, a 3.4-yr period binary hosting a 48 ms radio pulsar in an eccentric orbit around a Be star (Johnston et al. 1992). The TeV emission from this object is thought to be associated with the radio pulsar wind and its interaction with the radiation field and material around the Be-star, and shows variable unpulsed X-ray (Chernyakova et al. 2006b, 2009) and radio emission (Johnston et al. 1999, 2005), in particular close to the periastron passage due to the interaction between the pulsar and the Be disc. PSR B1259–63's X-ray emission is well described by an absorbed power law ($N_H = 5 \times 10^{21} \text{ cm}^{-2}$; $\Gamma \sim 1.2\text{--}1.8$), with an unabsorbed 1–10 keV flux varying between $0.1\text{--}3 \times 10^{-11} \text{ erg s}^{-1} \text{ cm}^{-2}$ (Chernyakova et al. 2006b, 2009).

LSI+61°303 and LS 5039 are both much closer binaries, with orbital periods of 26.5 and 3.9 d, respectively, hosting a very massive star (B and O types) and a compact object, the nature of which is still unknown for both sources (see Fig. 1 for a schematic view of LSI+61°303's orbit). Furthermore, LSI+61°303 and LS 5039 share the quality of (i) being the only two known γ -ray binaries

detected in the GeV band (Abdo et al. 2009a,b), (ii) they both show periodic TeV emission modulated by their orbital motion (Aharonian et al. 2006; Albert et al. 2008, 2009), (iii) variable X-ray emission (Bosch-Ramon et al. 2005, 2007; Sidoli et al. 2006; Paredes et al. 2007) correlated with the orbital motion, and (iv) they have a variable radio counterpart (see also below). Their X-ray emission is highly variable on a ks time-scale, and is for both objects characterized by an absorbed power-law spectrum (LSI+61°303: $N_H = 6 \times 10^{21} \text{ cm}^{-2}$ and $\Gamma \sim 1.4\text{--}1.9$; LS 5039: $N_H = 7 \times 10^{21} \text{ cm}^{-2}$ and $\Gamma \sim 1.4\text{--}1.6$), with a 1–10 keV unabsorbed flux varying between $0.4\text{--}1.5$ and $0.5\text{--}1.2 \times 10^{-11} \text{ erg s}^{-1} \text{ cm}^{-2}$, for LSI+61°303 and LS 5039, respectively (Sidoli et al. 2006; Esposito et al. 2007; Kishishita et al. 2009).

As the nature of the compact object is unknown in these two systems, it is not clear if their emission (especially in the TeV band) is due to a relativistic outflow from a rotational powered pulsar (as the case of PSR B1259–63) or accretion on to a black hole or a neutron star which might e.g. accelerate particles through a relativistic jet. Recently, a soft gamma repeater (SGR)-like burst detected from the direction of LSI+61°303 raised the possibility of this system hosting a magnetar, although this is so far a very controversial hypothesis (see Barthelmy et al. 2008; de Pasquale et al. 2008; Dubus & Giebels 2008; Muñoz-Arjonilla et al. 2008; Ray & Hartman 2008; Rea & Torres 2008). In the accretion scenario context, the recent evidence for TeV emission from the black hole binary Cyg X-1 is very exciting (Albert et al. 2007). However, the very high-energy phenomenology of Cyg X-1 appears different from that of these other sources: it has been in fact detected in TeV just once, and during a flaring state. The three other sources, instead, present persistent TeV emission modulated by the orbital motion, and which dominates their radiative outputs. For the new candidate TeV binary HESS J0632+057, it is still only very little known (e.g. no orbital period detected yet) to make any solid comparison (Aharonian et al. 2007, Hinton et al. 2009; Maier et al. 2009).

For LSI+61°303, extended radio emitting structures at angular extensions of $0.01\text{--}0.05$ arcsec have been reported (Massi et al. 2001, 2004). This discovery has earlier supported its microquasar interpretation, as a claim for a jet-like feature. However, a subsequent large Very Long Baseline Interferometry (VLBI) campaign (Dhawan et al. 2006) discovered rapid changes during the orbit, in the orientation of what seems to be a cometary tail consistent with being the result of a pulsar wind more than a jet-like structure. In fact, if due to a jet, the changing morphology of the radio emission along the orbit would require a highly unstable jet, and the shape of this structure is not expected to be reproduced orbit after orbit as current results indicate (Albert et al. 2008). Similarly, the discovery of a jet-like radio structure in LS 5039, initially prompted a microquasar interpretation (Paredes et al. 2001). However, Dubus (2006) showed that this extended radio emission could also be interpreted as the result of a pulsar wind, with no need to invoke a radio jet. Furthermore, recent Very Large Baseline Array (VLBA) observations showed that a microquasar scenario cannot easily explain the observed morphology changes of this radio extended feature (Ribó et al. 2008).

At this point, one of the long-standing open questions of high-energy astrophysics is: are these two peculiar binary systems accelerating charged particles until TeV energies, e.g. through the powerful jets of an accreting neutron star or black hole, as it might be the case of the TeV flares from Cyg X-1? Or is the TeV emission of these binaries instead related to a young and energetic rotational powered-pulsar as the case of PSR B1259–63? To try to address this question we performed deep *Chandra* observations of LSI+61°303

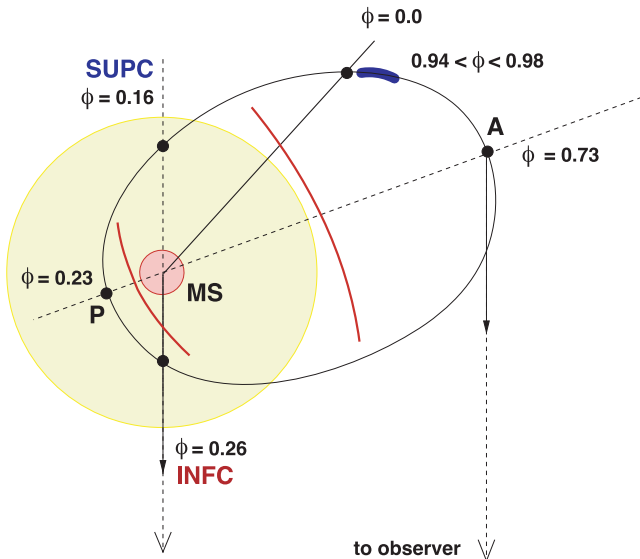


Figure 1. LSI+61°303's geometry considering the orbital solution of Casares et al. (2005). The phases for inferior conjunction (INFC), superior conjunction (SUPC), periastron (P), and apastron (A) are marked, and the inclination is not taken into account in the plot. The orbit (black solid line), the massive star (MS; in orange) and the equatorial Be disc (in yellow) are roughly to scale, assuming a disc radius seven times larger than the stellar radius. The blue thick line indicates the orbital phases spanned by our *Chandra* observation (adapted from Sierpowska-Bartosik & Torres 2009).

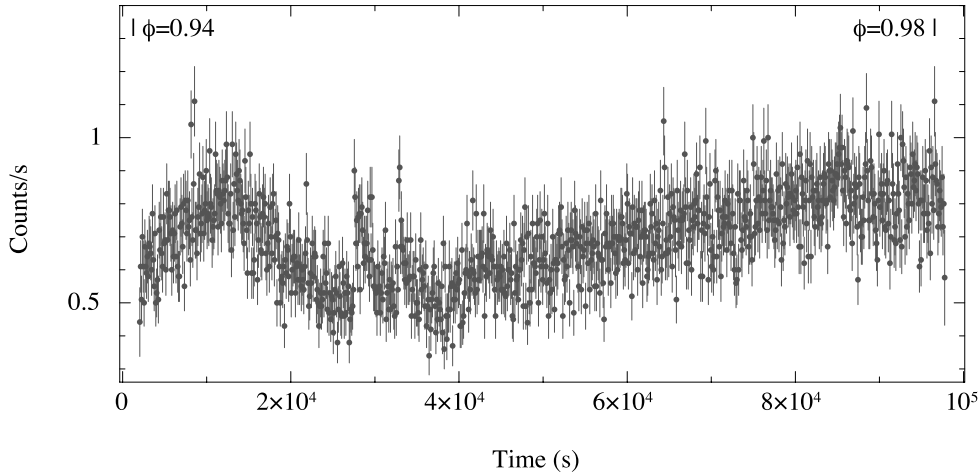


Figure 2. *Chandra* background-subtracted light curve of LSI+61°303 binned at 100 s, and in the 0.3–10 keV energy range. The orbital phase ϕ is also reported.

(this paper) and LS 5039 (Rea et al., in preparation) in search for pulsed X-ray emission with very low pulsed fraction (PF) (e.g. because contaminated by the wind-shock emission), which due to the higher background of previous X-ray observations might have been missed. In Section 2, we report on the LSI+61°303 observation and analysis, and we present our results in Section 3, followed by a discussion (Section 4).

2 OBSERVATION AND DATA ANALYSIS

The Advanced CCD Imaging Spectrometer (ACIS) camera on board of *Chandra* observed LSI+61°303 on 2008 November 14 (start time 11:09:58 UT; Obs-ID 10052) for an exposure time of 95.668 ks in continuous clocking (CC) mode (FAINT). The CC observing mode provides a time resolution of 2.85 ms and imaging along a single direction. The source was positioned in the back-illuminated ACIS-S3 CCD at the nominal target position. Standard processing of the data was performed by the *Chandra* X-ray Center to level 1 and level 2 (processing software DS ver. 7.6.11.9). The data were reprocessed using the CIAO software (ver. 4.1) and the *Chandra* calibration files (CALDB ver. 4.2.0).

Since in the CC mode the events are tagged with the times of the frame store, we corrected the times for the variable delay due to the spacecraft dithering and telescope flexure, starting from level 1 data and assuming that all photons were originally detected at the target position. Furthermore, data were filtered to exclude hot pixels, bad columns and possible afterglow events (residual charge from the interaction of a cosmic ray in the CCD). Photon arrival times are in TDB and were referred to the barycentre of the Solar system using the JPL-DE405 ephemeris.

In order to carry out a timing analysis, we extracted the events in the 0.3–10 keV energy range from a region of 5×5 pixels around the source position (RA 02:40:31.670, Dec. +61:13:45.11) to reduce the background contamination, while the source spectrum was extracted from a rectangular region of 5×25 pixels around the source position, and the background was taken independently from a source-free region in the same chip. We extracted the response matrix files (RMFs) and ancillary response files (ARFs), first creating a weighted image, rebinning by a factor of 8, then using it to build the RMF file using the MKACISRMF tool, with an energy grid

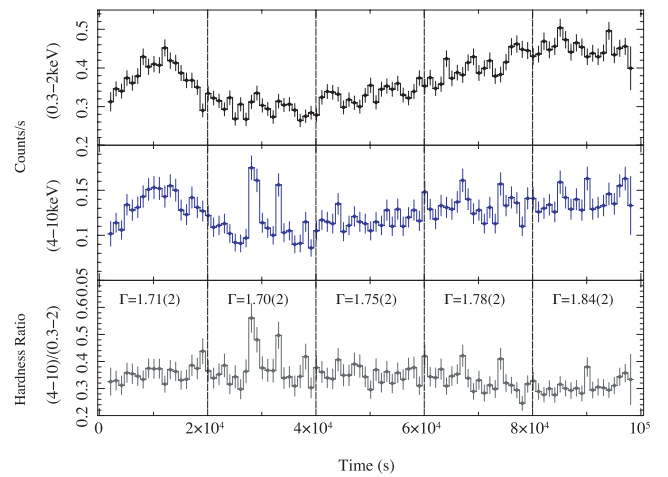


Figure 3. LSI+61°303 light curve in the 0.3–2 and 4–10 keV energy bands (top and middle rows, respectively), and their ratio (bottom row), all reported with a 1 ks bin time. Vertical lines separate the five intervals used in the analysis [of which we report the photon index (Γ) values].

ranging from 0.3 to 10 keV in 5 eV increments. Using this RMF and the aspect histogram created with the aspect solution for this observation (ASPHIST), we generated the appropriate ARF file for the source position. The source ACIS-S count rate in the 0.3–10 keV energy band was 0.648 ± 0.003 counts s^{−1} (the light curve is shown in Figs 2 and 3).

3 RESULTS

Using the orbital ephemeris of Casares et al. (2005), namely an orbital period of 26.4960 ± 0.0028 d and the zero-phase assumed at $T_0 = 2\,443\,366.775$ JD (defined as the radio phase; Gregory 2002), we calculated that the *Chandra* observation was performed while the neutron star was passing from phase 0.94 (at the start of the observation) to phase 0.98 (when it ends). Even if considering other orbital solutions (Grundstrom et al. 2007; Aragona et al. 2009), this corresponds for all assumed solutions to a part of the orbit soon after the apastron passage (see Fig. 1).

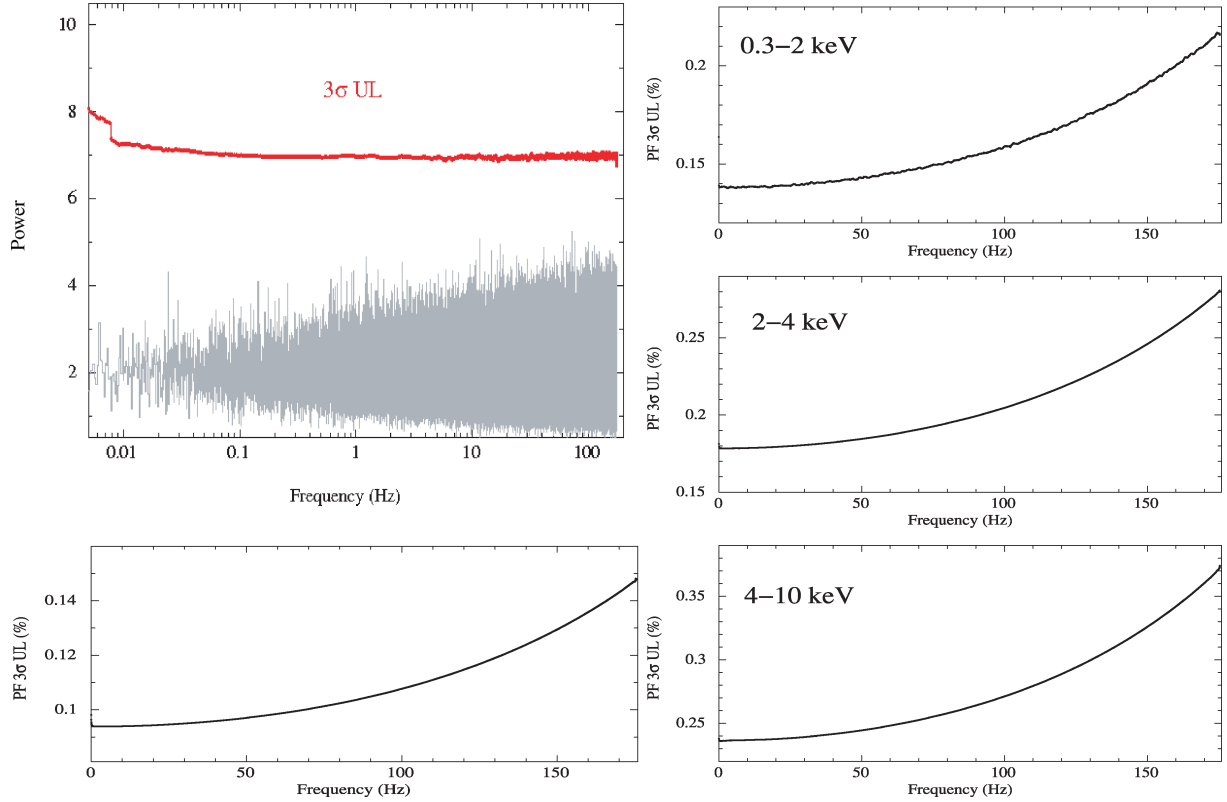


Figure 4. Left-hand panels: top row: power spectra of LSI+61°303 in the 0.3–10 keV energy band binned at 0.002 85 s with superimposed the 3σ upper limits on the detection of a periodic signal on top of the Poisson noise (we used here logarithmic scales to better show the low-frequency range). Bottom row: PF 3σ upper limits on the semi-amplitude of a sinusoidal signal. Right-hand panels: PF 3σ upper limits versus frequency in three different energy ranges (from top to bottom: 0.3–2, 2–4, 4–10 keV), calculated on the power spectrum binned at 0.002 85 s (left-hand panel) in the 0.005–175 Hz frequency range (see Section 3.1 for further details).

3.1 Timing analysis: pulsation search and flares

We searched for periodic and quasi-periodic signals with unprecedented sensitivity, thanks to the extremely low ACIS-S background (see for previous limits: Harrison et al. 2000; Sidoli et al. 2006;¹ Torres, Sierpowska-Bartosik & Rea 2010). Given the length of our observation (95 ks) and the timing resolution of the CC mode (0.00285 s), we could in principle search for periodic signals in the 10^{-5} –175 Hz frequency range (namely between the Nyquist frequency and half of the frequency resolution of our *Chandra* data; van der Klis 1989), however, our data were sensitive only in the 0.005–175 Hz frequency range, which we will then use all over this study. We studied the source power spectra performing fast fourier transforms (FFTs; see Fig. 4) using the *XRONOS* analysis software, and we did not find any periodic or quasi-periodic signal neither considering the total exposure time nor in each of the five time intervals shown in Fig. 3. Furthermore, we performed the same search dividing the data in three energy bands (0.3–2, 2–4 and 4–10 keV), again not finding any significant signal.

In particular, for computing reasons, we performed an average over nine FFTs with a bin time of 0.002 85 s (Fig. 4, top left-hand panel), resulting in 4 194 304 bins (~ 12 ks) for each of the nine averaged power spectra [the averaged power spectrum had a χ^2_ν dis-

tribution with 18 degree of freedom (d.o.f.)]. For the power spectra produced for the three different energy bands, given the lower number of counts, we could use a single FFT (their power spectrum had then a χ^2_ν distribution with 2 d.o.f.). We took into account the number of bins searched and the different d.o.f. of the noise power distribution (Vaughan et al. 1994; Israel & Stella 1996) in calculating the 3σ detection upper limits reported in Fig. 4. At very low frequencies, most probably due to the overall variability and flares present in the X-ray light curve (see Fig. 2), there is evidence for the onset of a red-noise component. We accounted for the red-noise component in the calculation of the detection significance by using a smoothing window technique (see Israel & Stella 1996 for further details).

We computed the 3σ upper limits on the sinusoid semi-amplitude PF, computed according to Vaughan et al. (1994) and Israel & Stella (1996), which ranges in the 0.3–10 keV energy band between $PF < 7$ –15 per cent (see Fig. 4, bottom left-hand panel). In Fig. 4 (right-hand column), we calculate the same PF limits as a function of the energy band. It is straightforward that the lower number of counts present in the energy-selected light curves causes the energy-dependent PF limits to be slightly larger than those derived using the whole data set. Note that given the long orbital period of this binary system (~ 26.5 d; Casares et al. 2005), we could reliably ignore the effect of such orbit during our pulsar searches, since our exposure time is much less than 10 per cent of orbital period (Vaughan et al. 1994).

We looked for the presence of SGR-like bursts by binning the counts in intervals of 0.1 s and searching for excesses above a count

¹ Note that the *RXTE* PF limits reported by Harrison et al. (2000) (~ 6 per cent) are calculated from the total count rate without correcting for the cosmic and instrumental background, which if corrected increases substantially the upper limit on the detectable PF to ~ 32 per cent.

threshold corresponding to a chance occurrence of 0.1 per cent (taking into account the total number of bins), but we did not find any significant short burst. On the other hand, on top of a slow variability of a factor of ~ 2 , we significantly detect two flares lasting ~ 3 and 1.5 ks (not unseen in this source: Sidoli et al. 2006; Paredes et al. 2007; Esposito et al. 2007; Smith et al. 2009) during the minimum of the light curve, with a rise-time of ~ 100 s, and peaking after about 28 and 33 ks from the observation start (see Figs 2 and 3).

3.2 Spatial analysis: search for extended emission

We studied the radial profile of LSI+61°303, using the CC mode one-dimensional (1D) imaging capability, to search for any evidence for extended X-ray emission (see also Paredes et al. 2007). We first generated an image of the 1D strip in the 0.3–10 keV band, and then subtracted the background count rate to remove instrumental and cosmic X-ray background. We then produced a 1D surface brightness distribution using the same method as for a two-dimensional radial profile, namely extracting photons from 125 annuli centred on the source position and of 2-pixel wide (~ 0.99 arcsec). We then simulated a *Chandra*/MARX point spread function (PSF) and extracted

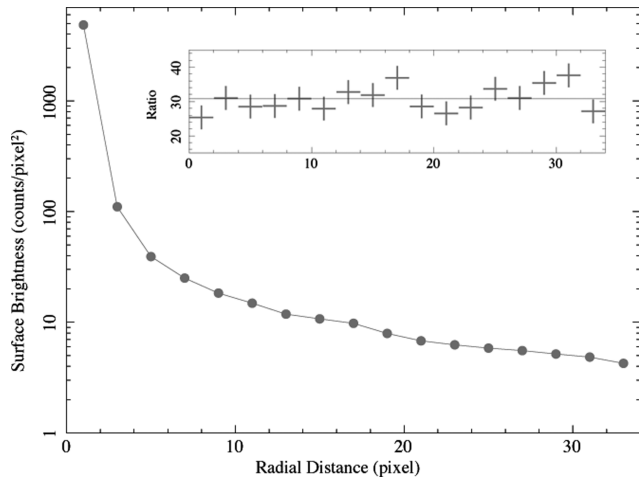
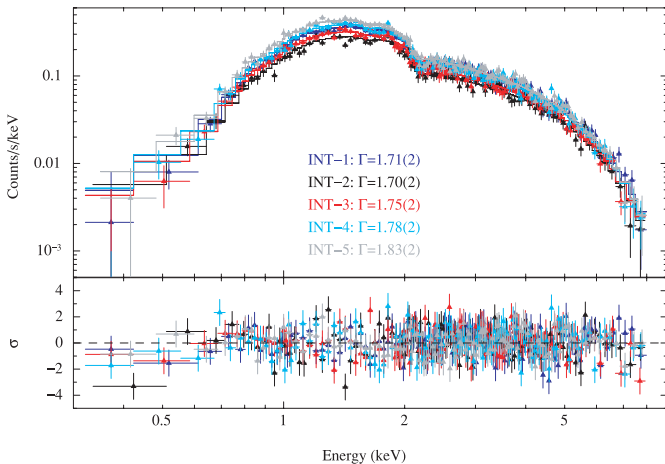


Figure 5. Surface brightness of LSI+61°303. 1 pixel corresponds to 0.495 arcsec. The inset represents the ratio between LSI+61°303 and RX J0806+1527's surface brightnesses.



photons from the same annular regions. We did not find evidence for a significant extended emission or structures within 30 arcsec around our target (see Fig. 5). As a further check, given the possible uncertainties of the 1D CC-mode PSF, we extracted with the same method a similar profile from a source observed in the same mode, and known to be point-like, namely the AMCVn RXJ0806+1527 (Obs-ID 4523; Israel et al. 2003). This source has a spectrum similar to our source, this is why we chose it as a good candidate for the PSF comparison. As shown in the inset of Fig. 5, we do not find any excess in the ratio between the surface brightness of LSI+61°303 and RXJ0806+1527, but only a constant flux difference of ~ 31 , which corresponds to the different brightness of these sources.

3.3 Spectral analysis: continuum modelling and search for spectral lines

The total spectrum, and the spectra relative to the five intervals shown in Fig. 3, were binned such to have at least 60 counts per bin and not to oversample the instrument spectral resolution by more than a factor of 3. We fit the total spectrum with an absorbed power law (typical for this source; see e.g. Bosch-Ramon et al. 2007) using the *XSPEC* software, which gives a reduced $\chi^2_v = 1.33$ for 173 d.o.f. The χ^2_v was not completely satisfactory, we then studied the spectrum dividing the total observation in five time intervals (see Figs 3 and 6) to investigate whether this was due to a significant spectral variability within the observation. This was indeed the case. We fit together the spectra of the five time intervals with an absorbed power-law function finding a $\chi^2_v = 1.01$ for 598 d.o.f, with the absorption value tied to be the same for all five spectra and the slope and normalization of the power laws free to vary. We find an absorption value of $N_H = (6.10 \pm 0.08) \times 10^{21} \text{ cm}^{-2}$, and a power-law index which varied from 1.70 to 1.83 depending on the time interval (see Fig. 3; all errors in the spectral values are reported at 1σ confidence level). The source 0.5–10 keV absorbed flux varied from the first to the fifth time interval (from left to right in Fig. 3): 8.5 ± 0.2 , 6.6 ± 0.2 , 7.2 ± 0.1 , 8.5 ± 0.2 and $9.0 \pm 0.1 \times 10^{-12} \text{ erg s}^{-1} \text{ cm}^{-2}$ (corresponding to unabsorbed fluxes of 1.2 ± 0.1 , 0.9 ± 0.1 , 1.0 ± 0.1 , 1.2 ± 0.1 and $1.3 \pm 0.1 \times 10^{-11} \text{ erg s}^{-1} \text{ cm}^{-2}$).

We also tried a fit using a *PEGPWR* model instead of the canonical *POWERLAW* model. The difference between the two is that in the former the normalization is calculated on an energy range given by

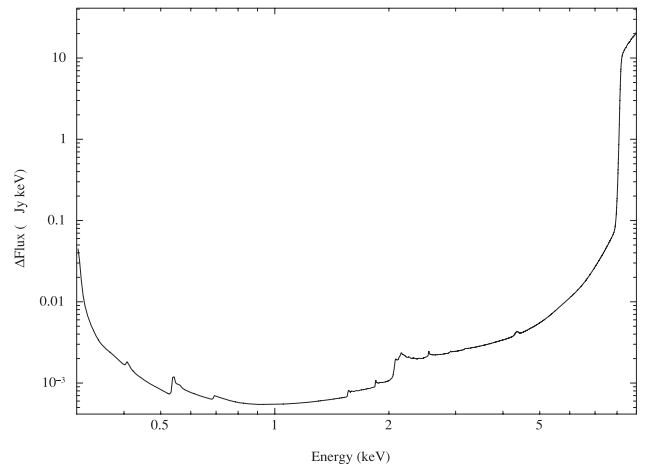


Figure 6. Left-hand panel: spectra of the five time intervals fitted with an absorbed power-law function (see Fig. 3 and Section 3.3 for details). Right-hand panel: 1σ sensitivity for the presence of spectral lines (defined as the 1σ limit for the detection of flux variability as a function of energy).

hand (we assumed 0.3–10 keV), while in the latter case it is calculated at 1 keV by default, and this can sometime cause a spurious Γ -normalization dependence. Using a PEGPWR, we found Γ and flux values consistent within 1σ with what previously reported for a simple power-law fit.

We also tried to leave the absorption value free to vary among the five spectra. We found an absorption value varying between $5.8(2)–6.2(2) \times 10^{21} \text{ cm}^{-2}$, with the same photon index or flux variation as the previous modelling. We then conclude that we do not detect any significant absorption variability within the sensitivity of our data. We do not find any evidence for absorption or emission features in the source averaged and time-resolved spectra. We derived upper limits as a function of the line energy and width by adding Gaussian lines to the continuum model both in absorption and in emission. For the total spectrum, the 3σ upper limit on the equivalent width of the presence of lines range between 50–550 eV depending on the energy (between 0.3–10 keV) and assumed line width ($\sigma_E = 0.05–0.5 \text{ keV}$). As a simpler visual plot, we report in Fig. 6 (right-hand panel), the 1σ upper limit on a detectable flux variation with respect to our continuum model as a function of the energy band, which corresponds to the detectability of spectral lines as broad as the energy-dependent instrument resolution on top of the continuum flux.

4 DISCUSSION

Thanks to this new *Chandra* observation (see Section 2), we inferred the deepest upper limits to date on the presence of X-ray pulsations from the TeV Be binary LSI+61°303 (PF $\lesssim 10$ per cent; see Section 3.1, and Fig. 4), while the compact object was close to the apastron of its orbit around the Be companion (see Fig. 1). Furthermore, we observed a strong flux variability during this observation (eventhough it was spanning a relatively small orbital phase in the 0.94–0.98 range), in particular LSI+61°303 emitted 2 ks time-scale flares during our observation, with a rather hard spectrum with respect to the source persistent emission (see Fig. 3 and Section 3.3). The accurate *Chandra* spatial resolution allowed us to study the X-ray spatial profile (although with the 1D CC-mode capability; see Section 3.2), which we found consistent with the instrumental PSF.

4.1 X-ray pulsed fractions of rotational-powered and accreting pulsars, comparison with our current limits

The detection of pulsations is the only unambiguous tracer for a secure determination of the pulsar nature of the compact objects hosted in LS 5039 and LSI+61°303. Deep searches for pulsations have been performed in the radio band at several frequencies, with the hope of detecting a fast spinning radio pulsar as in the case of the other TeV binary PSR B1259–63 (Johnston et al. 1999, 2005). However, no radio pulsations have been detected so far from any of these two sources. This is not surprising; in fact, the strong massive companion winds might have prevented radio pulsations to be detected because of the strong free–free absorption all over the orbits and/or the large and highly variable dispersion measure (DM) induced by the wind. In particular, in that respect, it is crucial to note that at periastron PSR B1259–63 does not show radio pulsations, and its periastron (given the large orbit, 3.4-yr period) has about the same dimension of the major axis of the orbit of LSI+61°303 (26-d period) and it is way larger than LS 5039’s orbit (4-d period), making very plausible the difficulty in detecting any radio pulsed emission from these closer binaries.

On the other hand, searches for pulsations in the X-ray band have many more chances of success than in the radio band. In fact, the X-ray pulsar beam is usually larger than the radio one, and the strong companion wind does not influence much the X-ray pulsed emission if present.

The deep PF upper limits we derived here (see Section 3 and Fig. 4) can be used to compare the X-ray emission of this TeV binary with that of isolated rotational-powered pulsars. X-ray pulsations from rotational powered pulsars have been detected in tens of objects, of which only 14 are to date also TeV emitters (see e.g. Mattana et al. 2009), due to the presence of an energetic pulsar wind nebula (PWN). All these TeV emitting pulsars known to date have high rotational power ($3 \times 10^{35} < \dot{E} < 5 \times 10^{38} \text{ erg s}^{-1}$), fast pulsations ($33 < P < 326 \text{ ms}$), young characteristic ages ($0.7 < \tau_c < 90 \text{ kyr}$), rather high magnetic fields ($10^{12} < B < 5 \times 10^{13} \text{ Gauss}$) and X-ray PFs $\gtrsim 18$ per cent.

The X-ray upper limits we derived here, namely PF ~ 10 per cent (see Fig. 4) for spin periods as fast as $\sim 5.6 \text{ ms}$ (much faster than the fastest rotational powered pulsar known to be a TeV emitter), clearly indicates that if the compact object hosted in LSI+61°303 is indeed a rotational-powered pulsar, its X-ray emission cannot be dominated by synchrotron emission from the pulsar magnetosphere alone, which might at most account for $\lesssim 10$ per cent of the emission, while the shock between the pulsar and the massive companion star winds is responsible for the remaining X-ray emission of the system.

In fact, in this pulsar scenario for LSI+61°303, radio, X-ray and γ -ray emission are (at least in part) thought to come from the region where the pulsar wind interacts with the wind of the Be companion star and/or (particularly, the γ -rays) from within the pulsar wind zone. This mostly depends on where the high-energy electrons generating the synchrotron and inverse Compton emission originate, the opacities therein and the geometry of the orbit (Sierpowska-Bartosik & Torres 2008).

In this respect, it should be mentioned that the TeV binary system hosting PSR B1259–63 does not show X-ray pulsations (Chernyakova et al. 2006b) during its periastron passage, with a limiting PF (derived as described in Section 3.1) of ~ 15 per cent (more details on that will be presented in the second paper of this series).² Also for this source, the X-ray emission might in fact be dominated by the interwind and/or pulsar-wind zones rather than being due to emission from the pulsar magnetosphere.

However, caution should be used here: in this line of reasoning, we are neglecting the possibility of a pulsar with a beam pointing away from our line of sight or spinning faster than $\sim 5.6 \text{ ms}$, and also that strong pulsations might have a transient appearance in only a small fraction of the orbital motion, and in such small fraction being instead dominated by the pulsar magnetosphere. On the other hand, if we assume that a putative transient pulsed emission is diluted in part of the orbit by Compton scattering, from the rise times of the flares $t \sim R_C \tau/c \sim 100 \text{ s}$ (see Fig. 2; c is the velocity of light), and assuming an optical depth $\tau \gg 1$, we can derive that the Compton scattering sphere radius should be $R_C \ll 3 \times 10^{12} \text{ cm}$, which is about half of semimajor axis of LSI+61°303’s orbit. In this respect, our observations were performed in a part of the orbit (soon after the apastron passage; see Fig. 1), where the detection of transient pulsations should have been more favourable, and the

² Note that Chernyakova et al. (2006b) report a limiting PF of 2 per cent, however these authors did not report the exact definition they used for PF, the energy range and background subtraction method they used. Possible differences in these assumptions might be the cause of such discrepancy.

Compton scattering highly reduced with respect to other parts of the orbit closer to the massive companion.

Considering instead the accreting neutron star scenario (in the black hole case we obviously do not expect pulsations at all hence we will not discuss this possibility which is of course open), low PFs are not unexpected. In particular, in many cases, the pulsed X-ray emission coming from the accretion column might represent only a small fraction of the total X-ray emission which can also have a dominant unpulsed component coming from the accretion disc and/or the neutron star surface.

4.2 Flares and flux/spectral variability on ks time-scales

A large variety of flares on several time-scales (from seconds to days) have been observed to date from both neutron star and black hole binary systems. While in the accretion scenario flares are easily explainable as changes in the accretion rate from the companion star, or accretion disc, towards the compact object, this kind of X-ray variability has never been observed in isolated rotation powered-pulsars.³

In the rotational-powered pulsar scenario, the ks variability we observe here indicates that the interaction of the putative pulsar and the stellar wind change at distance scales which are smaller than the size of the binary orbit; put otherwise, that the mechanism by which the variability is generated has a shorter-than-orbital time-scale. To interpret the short time-scale variability (of the order of ks, and in the form of hard flares) seen in our *Chandra* data [also seen earlier in *XMM-Newton* observations by Sidoli et al. (2006) and Chernyakova, Neronov & Walter (2006a)], it seems reasonable to invoke clumpiness of the stellar wind (see ideas by Neronov & Chernyakova 2007; Zdziarski, Neronov & Chernyakova 2008).

If one assumes that the power output in the pulsar wind is constant in ks time-scales (which may not be necessarily true, due to inhomogeneities in the pulsar wind zone, and if so, ks variability could be related to it), the distance scale related to the fast variability has to be associated with the pulsar wind interactions with clumps of the Be stellar wind. In the latter case, the size, mass and number density of the clumps imprint their signal on the X-ray emission. The distance scale relevant for this fast variability can be estimated as

$$R_w \sim v \Delta t \sim 10^{11} \left(\frac{v}{10^7 \text{ cm s}^{-1}} \right) \left(\frac{\Delta t}{10 \text{ ks}} \right) \text{ cm},$$

where v is typical velocity scale (e.g. the orbital velocity of the pulsar or the speed of the stellar wind).

The stellar wind of Be stars, like the one present in LS I +61°303, is typically assumed to have two components, one related with a polar contribution, and the other, with an equatorial disc (e.g. Waters et al. 1988). The polar wind is radiatively driven (e.g. Castor & Lamers 1979). The equatorial wind is instead assumed to have an homogeneous velocity law $V_{\text{eq}}(r) = V_0^{\text{eq}} (r/R_s)^m$ where $m \sim 1.25$, R_s is the stellar radius and $V_0^{\text{eq}} = 5 \text{ km s}^{-1}$. These authors further assume that the terminal velocity of the equatorial wind is $V_{\infty}^{\text{eq}} \sim \text{few } 100 \text{ km s}^{-1}$, so that it is about a factor of at least 10 times smaller than the terminal velocity of the polar component, $V_{\infty}^{\text{polar}}$. Clumpiness in this wind can make the region of collision between the pulsar and stellar outflows to loose coherence, leading to the

disappearance of a regular bow-shaped surface. If so happens, the escape time-scale of the pulsar wind mixed with the stellar wind can be written as

$$t_{\text{esc}} \sim D/v_{\text{wind}} \sim 100 \left(\frac{10^{12} \text{ cm}}{D} \right) \left(\frac{10^7 \text{ cm s}^{-1}}{v_{\text{wind}}} \right) \text{ ks}$$

(slowed down from the case in which electrons move along the shock with the plasma velocity $c/3$, the drift velocity in the direction parallel to the shock surface), and where v_{wind} can take typical V_{∞}^{eq} or $V_{\infty}^{\text{polar}}$ values.

Even with this time-scale, clumps can cool electrons via inverse Compton. This statement can be entertained after comparing the cooling time-scale of electrons of about 10 MeV, which would be responsible via inverse Compton emission of X-ray photons between 1 and 10 keV. Assuming that electrons diffuse in disordered magnetic field in the clump, one can estimate the Bohm-diffusion-regime escape time as

$$t_{\text{diff}} \simeq 3 \times 10^6 \left(\frac{R_w}{10^{11} \text{ cm}} \right)^2 \left(\frac{B}{1 \text{ G}} \right) \left(\frac{10 \text{ MeV}}{E} \right) \text{ s},$$

thus, clumps with such magnetic fields can retain electrons over significant time-scales. The losses by synchrotron and inverse Compton are

$$t_{\text{synch}} \simeq 3 \times 10^5 \left(\frac{1 \text{ G}}{B} \right)^2 \left(\frac{10 \text{ MeV}}{E} \right) \text{ s},$$

$$t_{\text{IC}} \simeq 10^4 \left(\frac{L_*}{10^{38} \text{ erg s}^{-1}} \right) \left(\frac{D}{10^{12} \text{ cm}} \right)^2 \left(\frac{10 \text{ MeV}}{E} \right) \text{ s}$$

with L_* being the luminosity of the star. For nominal values of the parameters, then, an inverse Compton cooling is possible.

Using the expression for the inverse Compton and synchrotron time-scales one finds that if the magnetic field does not significantly rise from its PWN value of $\sim 1 \text{ G}$ towards the centre of the system, inverse Compton losses dominate at the inner region. However, synchrotron emission quickly dominate the farther out of the system electrons are, and can contribute to the overall X-ray emission detected, given the nebula an onion-like structure where losses dominance change. Depending on the location of the inhomogeneity and value of magnetic field, relative contributions of inverse Compton and synchrotron X-rays can vary.

Finally, if clumps can be described by variations in density, and if the typical density of a clump in the wind is $n_{\text{clump}} \sim 10^{10} \text{ cm}^{-3}$ and its size is $R_{\text{clump}} \sim 10^{11} \text{ cm}$, then $\delta N_H \sim n_{\text{clump}} \times R_{\text{clump}} \sim 10^{21} \text{ cm}^{-2}$. We did not find significant N_H variability within our data, however the strong dependence between N_H , Γ and the power-law normalization, intrinsic to the power-law modelling, might have hidden this variability in an increase of the hardness of the emission, as seen in our Figs 3 and 6 (see also Smith et al. 2009).

4.3 Limits on the presence of diffuse emission

Studying the 1D *Chandra* PSF, we did not find evidence for X-ray diffuse emission (see Fig. 5 and Section 3.2). For a quantitative comparison of our limits with the hint for diffuse emission observed by Paredes et al. (2007; see their Section 2.3), we followed their analysis extracting the counts in an annular region of 5–12.5 arcsec radii. Assuming an absorbed power-law spectrum with $N_H = 6.1 \times 10^{21} \text{ cm}^{-2}$ and $\Gamma = 2$, we inferred a 3σ limiting unabsorbed flux for the presence of X-ray diffuse emission of $\sim 1 \times 10^{-14} \text{ erg s}^{-1} \text{ cm}^{-2}$

³ Note that magnetars do show X-ray flaring activity on several time-scales, but in fact they are not rotational-powered while their emission (flaring and persistent) is due to the presence and instability of their ultrastrong magnetic fields (see Mereghetti 2008 for a recent review).

in the 0.3–10 keV energy range.⁴ Using the same assumptions we made, the flux of the diffuse emission proposed by Paredes et al. (2007) would be $\sim 2 \times 10^{-14}$ erg s⁻¹ cm⁻², well above our detection limit.

We caveat that if a putative extended emission (Paredes et al. 2007) shows a long-term variability, our non-detection can be due to a different observing epoch with respect to the original *Chandra* observation which hinted at the presence of diffuse emission.

5 SUMMARY

With the *Chandra* observation we report here, we inferred the deepest upper limits to date on the presence of X-ray pulsations from the TeV Be binary LSI+61°303 (PF \lesssim 10 per cent; with a strong energy and frequency dependence, see Fig. 4), while the compact object was close to the apastron of its orbit around the Be companion (see Fig. 1). These PF limits are deeper than the PF measured from any isolated rotational-powered pulsar, in particular from those emitting in the TeV range, while they are well in line with what is observed from accreting neutron star binaries (although we do not see clear signs of accretion, as e.g. spectral lines). Hence, if hosting a rotational-powered pulsar, LSI+61°303's X-ray emission cannot be driven by the same processes as for a similar isolated case (with the caveats discussed in Section 4.1 though), while indeed a major contribution to its X-ray emission should come from the shock between the pulsar and Be star winds. This is probably also the case for PSR B1259–63. The ks time-scale flares we saw in this *Chandra* observation of LSI+61°303 show a harder spectrum with respect to the source emission, and can be explained in an accretion scenario by variability in the accretion rate, while in the rotational-powered pulsar one, as the interaction between the pulsar wind and clumps in the Be wind.

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⁴ Note that to infer the diffuse flux, Paredes et al. (2007) assumed the spectrum of their *Chandra* observation, $\Gamma = 1.25$, which was highly affected by pile-up. We then prefer to assume $\Gamma = 2$, the typical value for a PWNe.

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